THE CATHOLIC UNIVERSITY OF AMERICA
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POSITION CONTROL OF REDUNDANT MANIPULATORS USING AN ADAPTIVE ERROR-BASED CONTROL SCHEME

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REPORT SUMMARY

This is a semiannual report presenting the research results obtained from the research grant entitled "Development of Advanced Control Schemes for Telerobot Manipulators," funded by the Goddard Space Flight Center (NASA) under a research grant with Grant Number NAG 5-1124, for the period between February 1st, 1990 and July 31, 1990.

*A Cartesian-space control scheme is developed to control the motion of kinematically redundant manipulators with 7 degrees of freedom (***DOF***). The control scheme consists mainly of proportional-derivative (***PD***) controllers whose gains are adjusted by an adaptation law driven by the errors between the desired and actual trajectories. The adaptation law is derived using the concept of model reference adaptive control (***MRAC***) and Lyapunov direct method under the assumption that the manipulator performs non-compliant and slowly-varying motions. The developed control scheme is computationally efficient because its implementation does not require the computation of the manipulator dynamics. Computer simulation performed to evaluate the control scheme performance is presented and discussed.*

1 Introduction

Considerable research effort has been spent to study kinematics and control of kinematically redundant[1] manipulators [1]-[8] during the last decade. In [1], the problem of programming and control of redundant manipulators was investigated and the method of extended Jacobian was applied to optimize an object function. The concept of *self motion* was introduced by the authors of [2], who proposed a method to resolve the redundancy by directly controlling a set of self-motion parameters. The global optimization problem of joint rates and kinetic energy in redundant manipulators was considered in [5], and the results of the global optimization results were compared with those of the local one. The method of pseudo-inverse was reviewed in [6] for application in redundant robots. Recognizing the challenging difficulties in the control of position and force because of redundancy, numerous researchers have focused their effort on developing control schemes for redundant robot manipulators. Cartesian-space control schemes were developed in [3] to control position/force of redundant manipulators, and in [4] to control a hydraulic redundant robot. Joint-space and Cartesian-space adaptive control schemes were developed in [7] and in [10], respectively for a redundant telerobot manipulator. Recently the so-called *configuration control* which utilizes the manipulator redundancy was introduced in [8] to control the manipulator configuration directly in task space.

In this report, we first present the development of a Cartesian-space adaptive control scheme for redundant manipulators. We then present and discuss the computer simulation performed to study the performance of the developed control scheme implemented to control the non-compliant motion of a 7 DOF redundant manipulator. Finally a conclusion will describe some current research activities and outline the future research direction. Matrix notations used in this report are: $\mathbf{M}^T$=transpose of the matrix $\mathbf{M}$; $\mathbf{0}_n$=(nxn) matrix whose elements are all zero; $\mathbf{I}_n$=(nxn) identity matrix; and $tr[\mathbf{M}]$=trace of matrix $\mathbf{M}$.

2 The Error-Based Adaptive Control Scheme

Figure 1 presents the control scheme proposed for controlling the non-compliant motion of a 7 DOF redundant manipulator. As the figure shows, the actual joint variables measured by joint position sensors, are transformed into the corresponding Cartesian variables via the forward kinematic transformation. The errors between the actual and desired Cartesian variables serve as inputs to a PD controller whose gains are adjusted by an adaptation law to be derived. The Cartesian forces available at the output of the PD controllers are transformed into the corresponding joint forces using the Jacobian transpose.

The dynamics of the 7 DOF redundant manipulator performing non-compliant mo-

[1]The term "redundant" is often used instead of "kinematically redundant".

tion can be expressed in Cartesian space as [10]

$$\mathbf{F}(t) = \boldsymbol{\Lambda}(\mathbf{x}, \dot{\mathbf{x}})\, \ddot{\mathbf{x}}(t) + \boldsymbol{\Phi}(\mathbf{x}, \dot{\mathbf{x}})\, \dot{\mathbf{x}}(t) + \boldsymbol{\Gamma}(\mathbf{x}, \dot{\mathbf{x}})\, \mathbf{x}(t) \tag{1}$$

where $\mathbf{x}(t)$ denotes the (6x1) Cartesian position[2] vector of the slave arm end-effector, and $\mathbf{F}(t)$, the (6x1) Cartesian force applied to the end-effector. $\boldsymbol{\Lambda}(\mathbf{x}, \dot{\mathbf{x}})$, a symmetric positive-definite matrix, $\boldsymbol{\Phi}(\mathbf{x}, \dot{\mathbf{x}})$ and $\boldsymbol{\Gamma}(\mathbf{x}, \dot{\mathbf{x}})$ are of order (6x6) with elements that are highly complex nonlinear functions of $\mathbf{x}$ and $\dot{\mathbf{x}}$.

The outputs of the PD controller constitute the Cartesian force vector $\mathbf{F}(t)$ computed by

$$\mathbf{F}(t) = \mathbf{K}_p(t)\, \mathbf{x}_e(t) + \mathbf{K}_d(t)\, \dot{\mathbf{x}}_e(t) \tag{2}$$

where $\mathbf{x}_e(t)$ given by

$$\mathbf{x}_e(t) = \mathbf{x}_d(t) - \mathbf{x}(t) \tag{3}$$

denotes the Cartesian error vector between the actual Cartesian position vector $\mathbf{x}(t)$ and the desired Cartesian position vector $\mathbf{x}_d(t)$, $\mathbf{K}_p(t)$ and $\mathbf{K}_d(t)$, are gain matrices of the proportional and derivative controllers, respectively.

Substituting (2) into (1) yields

$$\boldsymbol{\Lambda}\, \ddot{\mathbf{x}}_e + (\boldsymbol{\Phi} + \mathbf{K}_d)\, \dot{\mathbf{x}}_e + (\boldsymbol{\Gamma} + \mathbf{K}_p)\, \mathbf{x}_e = \boldsymbol{\Lambda}\, \ddot{\mathbf{x}}_d + \boldsymbol{\Phi}\, \dot{\mathbf{x}}_d + \boldsymbol{\Gamma}\, \mathbf{x}_d \tag{4}$$

where the dependent variables of the matrices and vectors were dropped for simplicity.

The state equation of (4) can be obtained by defining the state variable vector $\mathbf{z}(t)$

$$\mathbf{z}(t) = \left[\mathbf{x}_e^T(t) \quad \dot{\mathbf{x}}_e^T(t)\right]^T. \tag{5}$$

so that from (4), we obtain

$$\dot{\mathbf{z}}(t) = \begin{bmatrix} \mathbf{0}_6 & \mathbf{0}_6 \\ -\mathbf{B}_1 & -\mathbf{B}_2 \end{bmatrix} \mathbf{z}(t) + \begin{bmatrix} \mathbf{0}_6 & \mathbf{0}_6 & \mathbf{0}_6 \\ \mathbf{B}_3 & \mathbf{B}_4 & \mathbf{I}_6 \end{bmatrix} \mathbf{u}(t) \tag{6}$$

where

$$\mathbf{B}_1 = \boldsymbol{\Lambda}^{-1}(\boldsymbol{\Gamma} + \mathbf{K}_p), \quad \mathbf{B}_2 = \boldsymbol{\Lambda}^{-1}(\boldsymbol{\Phi} + \mathbf{K}_d), \tag{7}$$

and

$$\mathbf{B}_3 = \boldsymbol{\Lambda}^{-1}\, \boldsymbol{\Gamma}, \quad \mathbf{B}_4 = \boldsymbol{\Lambda}^{-1}\, \boldsymbol{\Phi}, \tag{8}$$

and

$$\mathbf{u}(t) = \left[\mathbf{x}_d^T(t) \quad \dot{\mathbf{x}}_d^T(t) \quad \ddot{\mathbf{x}}_d^T(t)\right]^T. \tag{9}$$

In order to achieve a minimal computational burden in real-time control, a *reference model* which characterizes the desired manipulator performance, should be selected as follows:

$$\ddot{x}_{ei}(t) + 2\, \xi_i\, \omega_i\, \dot{x}_{ei}(t) + \omega_i^2\, x_{ei}(t) = 0 \tag{10}$$

[2]In this report, position implies both position and orientation and force implies both force and torque.

where ξ_i and ω_i denote the damping ratio and the natural frequency of x_{ei}, and $x_{ei}(t)$ for i=1,2,...,7 are the elements of the tracking error vector $\mathbf{x}_e(t) = [x_{e1}(t)\ x_{e2}(t) \ldots x_{e6}(t)]^T$. As seen from Equation (10), the reference model is a linear time-invariant system consisting of 6 uncoupled systems, each of which represents the desired error behavior in the corresponding Cartesian position.

From (10), the state equation of the reference model can be obtained as

$$\dot{\mathbf{z}}_m(t) = \boldsymbol{\Delta}\, \mathbf{z}_m(t) = \begin{bmatrix} \mathbf{0}_6 & \mathbf{I}_6 \\ -\boldsymbol{\Delta}_1 & -\boldsymbol{\Delta}_2 \end{bmatrix} \mathbf{z}_m(t), \tag{11}$$

where $\boldsymbol{\Delta}_1$=diag(ω_i^2) and $\boldsymbol{\Delta}_2$=diag($2\xi_i\omega_i$) are constant (6x6) diagonal matrices, and

$$\mathbf{z}_m(t) = \left[\mathbf{x}_m^T(t) \quad \dot{\mathbf{x}}_m^T(t)\right]^T \tag{12}$$

with

$$\mathbf{x}_m = (x_{e1}\ x_{e2}\ \ldots x_{e6})^T. \tag{13}$$

Now solving (11), we obtain

$$\mathbf{z}_m(t) = e^{\boldsymbol{\Delta} t}\, \mathbf{z}_m(0) \tag{14}$$

where the initial value of $\mathbf{z}_m(t)$ is denoted by $\mathbf{z}_m(0)$. Here if we assume that the initial values of the actual and desired Cartesian position and velocity vectors are identical, i.e. $\mathbf{z}_m(0) = 0$, then $\mathbf{z}_m(t) = 0$. Otherwise we can properly select ξ_i and ω_i so that all eigenvalues of $\boldsymbol{\Delta}$ are stable to make $\mathbf{z}_m(t) \to 0$ as $t \to \infty$.

Next the adaptation error vector $\mathbf{E}$(t) is defined as

$$\mathbf{E}(t) = \mathbf{z}_m(t) - \mathbf{z}(t). \tag{15}$$

Then from (6) and (11), an *error system* is obtained by

$$\begin{aligned} \dot{\mathbf{E}}(t) &= \begin{bmatrix} \mathbf{0}_6 & \mathbf{I}_6 \\ -\boldsymbol{\Delta}_1 & -\boldsymbol{\Delta}_2 \end{bmatrix} \mathbf{E}(t) + \begin{bmatrix} \mathbf{0}_6 & \mathbf{0}_6 \\ \mathbf{B}_1 - \boldsymbol{\Delta}_1 & \mathbf{B}_2 - \boldsymbol{\Delta}_2 \end{bmatrix} \mathbf{z}(t) \\ &\quad + \begin{bmatrix} \mathbf{0}_6 & \mathbf{0}_6 & \mathbf{0}_6 \\ -\mathbf{B}_3 & -\mathbf{B}_4 & -\mathbf{I}_6 \end{bmatrix} \mathbf{u}(t). \end{aligned} \tag{16}$$

Now a Lyapunov function $v(t)$ is selected such that

$$\begin{aligned} v(t) &= \mathbf{E}^T\mathbf{P}\mathbf{E} + tr\left[(\mathbf{B}_1 - \boldsymbol{\Delta}_1)^T\boldsymbol{\Psi}_1(\mathbf{B}_1 - \boldsymbol{\Delta}_1)\right] \\ &\quad + tr\left[(\mathbf{B}_2 - \boldsymbol{\Delta}_2)^T\boldsymbol{\Psi}_2(\mathbf{B}_2 - \boldsymbol{\Delta}_2)\right] + tr[\mathbf{B}_3^T\boldsymbol{\Psi}_3\mathbf{B}_3] + tr[\mathbf{B}_4^T\boldsymbol{\Psi}_4\mathbf{B}_4], \end{aligned} \tag{17}$$

where $\mathbf{P}$ and $\boldsymbol{\Psi}_i$ for i=1,2,...,4, are positive definite matrices which will be determined.

After differentiating (17) with respect to time and simplifying the resulting expression, we arrive at

$$\begin{aligned} \dot{v}(t) &= \mathbf{E}^T(\mathbf{P}\boldsymbol{\Delta} + \boldsymbol{\Delta}^T\mathbf{P})\mathbf{E} + 2tr\left[(\mathbf{B}_1 - \boldsymbol{\Delta}_1)^T(\boldsymbol{\Upsilon}\mathbf{x}_e^T + \boldsymbol{\Psi}_1\dot{\mathbf{B}}_1)\right] - 2tr\left[\mathbf{B}_3^T(\boldsymbol{\Upsilon}\mathbf{x}_d^T - \boldsymbol{\Psi}_3\dot{\mathbf{B}}_3)\right] \\ &\quad + 2tr\left[(\mathbf{B}_2 - \boldsymbol{\Delta}_2)^T(\boldsymbol{\Upsilon}\dot{\mathbf{x}}_e^T + \boldsymbol{\Psi}_2\dot{\mathbf{B}}_2)\right] - 2tr\left[\mathbf{B}_4^T(\boldsymbol{\Upsilon}\dot{\mathbf{x}}_d^T - \boldsymbol{\Psi}_4\dot{\mathbf{B}}_4)\right] \end{aligned} \tag{18}$$

where

$$\boldsymbol{\Upsilon} = [\mathbf{P}_2\ \ \mathbf{P}_3]\mathbf{z}(t) = -\mathbf{P}_2\mathbf{x}_e - \mathbf{P}_3\dot{\mathbf{x}}_e \tag{19}$$

and $\mathbf{P}$ is given by

$$\mathbf{P} = \begin{bmatrix} \mathbf{P}_1 & \mathbf{P}_2 \\ \mathbf{P}_2 & \mathbf{P}_3 \end{bmatrix} \tag{20}$$

and we note that $\mathbf{z}_m(t) = 0$ results in $\mathbf{E}(t) = -z(t)$.

Now if ξ_i and ω_i of (10) are selected so that $\boldsymbol{\Delta}$ is a *Hurwitz* matrix [9], i.e. all eigenvalues of $\boldsymbol{\Delta}$ have negative real parts, then according to *Lyapunov theorem*, there exists a positive definite symmetric matrix $\mathbf{P}$ satisfying the Lyapunov equation given by

$$\mathbf{P}\boldsymbol{\Delta} + \boldsymbol{\Delta}^T\mathbf{P} = -\mathbf{Q} \tag{21}$$

for any given positive-definite symmetric matrix $\mathbf{Q}$.

Now in (18) letting

$$\boldsymbol{\Upsilon}\mathbf{x}_e^T + \boldsymbol{\Psi}_1\dot{\mathbf{B}}_1 = \boldsymbol{\Upsilon}\dot{\mathbf{x}}_e^T + \boldsymbol{\Psi}_2\dot{\mathbf{B}}_2 = 0;\ \ \boldsymbol{\Upsilon}\mathbf{x}_d^T - \boldsymbol{\Psi}_3\dot{\mathbf{B}}_3 = \boldsymbol{\Upsilon}\dot{\mathbf{x}}_d^T - \boldsymbol{\Psi}_4\dot{\mathbf{B}}_4 = 0, \tag{22}$$

changes (18) to

$$\dot{v}(t) = -\mathbf{E}^T\mathbf{Q}\mathbf{E} \tag{23}$$

which is a negative definite function of $\mathbf{E}(t)$. Also from (22), we obtain

$$\dot{\mathbf{B}}_1 = -\boldsymbol{\Psi}_1^{-1}\boldsymbol{\Upsilon}\mathbf{x}_e^T;\ \ \dot{\mathbf{B}}_2 = -\boldsymbol{\Psi}_2^{-1}\boldsymbol{\Upsilon}\dot{\mathbf{x}}_e^T;\ \ \dot{\mathbf{B}}_3 = \boldsymbol{\Psi}_3^{-1}\boldsymbol{\Upsilon}\mathbf{x}_d^T;\ \ \dot{\mathbf{B}}_4 = \boldsymbol{\Psi}_4^{-1}\boldsymbol{\Upsilon}\dot{\mathbf{x}}_d^T. \tag{24}$$

According to (17), since $\mathbf{P}$ is a positive definite matrix by properly selecting $\boldsymbol{\Delta}$ and $\mathbf{Q}$, the error system described in (16) is asymptotically stable if we can show that $\boldsymbol{\Psi}_i$ for i=1,2,...,4, are also positive definite matrices. In other words, the *adjustable system* (6) will follow the reference model very closely, or $\mathbf{z}(t)$ approaches $\mathbf{z}_m$ asymptotically as $t \to \infty$.

Before proceeding, we assume that the end-effector of the manipulator performs slowly varying motion so that the elements of $\boldsymbol{\Lambda}$, $\boldsymbol{\Phi}$ and $\boldsymbol{\Gamma}$ can be considered *almost constant.* As a result, from (7) and (8) we have

$$\dot{\mathbf{B}}_1 \simeq \boldsymbol{\Lambda}^{-1}\dot{\mathbf{K}}_p;\ \ \dot{\mathbf{B}}_2 \simeq \boldsymbol{\Lambda}^{-1}\dot{\mathbf{K}}_d;\ \ \dot{\mathbf{B}}_3 \simeq 0;\ \ \dot{\mathbf{B}}_4 \simeq 0. \tag{25}$$

Substituting (25) into (24) yields

$$\boldsymbol{\Lambda}^{-1}\dot{\mathbf{K}}_p = -\boldsymbol{\Psi}_1^{-1}\boldsymbol{\Upsilon}\mathbf{x}_e^T;\ \ \boldsymbol{\Lambda}^{-1}\dot{\mathbf{K}}_d = -\boldsymbol{\Psi}_2^{-1}\boldsymbol{\Upsilon}\dot{\mathbf{x}}_e^T, \tag{26}$$

and

$$0 \simeq \boldsymbol{\Psi}_3^{-1}\boldsymbol{\Upsilon}\mathbf{x}_d^T;\ \ 0 \simeq \boldsymbol{\Psi}_4^{-1}\boldsymbol{\Upsilon}\dot{\mathbf{x}}_d^T. \tag{27}$$

Now in (26), if we let

$$\boldsymbol{\Psi}_1 = -\frac{1}{\beta_1}\boldsymbol{\Lambda};\ \ \boldsymbol{\Psi}_2 = -\frac{1}{\beta_2}\boldsymbol{\Lambda}, \tag{28}$$

where β_1 and β_2 are arbitrary positive scalars, and solving for $\dot{\mathbf{K}}_p$ and $\dot{\mathbf{K}}_d$, we arrive at

$$\dot{\mathbf{K}}_p = \beta_1 \boldsymbol{\Upsilon} \mathbf{x}_e^T; \;\; \dot{\mathbf{K}}_d = \beta_2 \boldsymbol{\Upsilon} \dot{\mathbf{x}}_e^T. \tag{29}$$

In (28), obviously $\boldsymbol{\Psi}_1$ and $\boldsymbol{\Psi}_2$ are positive definite matrices that can be considered as nearly constant because $\boldsymbol{\Lambda}$ is positive definite and slowly time-varying. In addition, $\boldsymbol{\Psi}_3$ and $\boldsymbol{\Psi}_4$ should be chosen to be positive definite matrices whose determinants approach ∞ in order to satisfy (27). To achieve this, we can select $\boldsymbol{\Psi}_3$ and $\boldsymbol{\Psi}_4$ to be diagonal matrices whose main diagonal elements assume very large and positive values.

Now integrating both sides of the equations given in (29) results in

$$\mathbf{K}_p(t) = \mathbf{K}_p(0) + \beta_1 \int_0^t (\mathbf{P}_2 \mathbf{x}_e + \mathbf{P}_3 \dot{\mathbf{x}}_e) \mathbf{x}_e^T dt \tag{30}$$

and

$$\mathbf{K}_d(t) = \mathbf{K}_d(0) + \beta_2 \int_0^t (\mathbf{P}_2 \mathbf{x}_e + \mathbf{P}_3 \dot{\mathbf{x}}_e) \dot{\mathbf{x}}_e^T dt \tag{31}$$

where $\mathbf{K}_p(0)$ and $\mathbf{K}_d(0)$ are initial conditions of $\mathbf{K}_p(t)$ and $\mathbf{K}_d(t)$, respectively and can be set arbitrarily.

The development of the adaptive controller is now completed. As shown in (30) and (31), the adaptation law is designed based on the errors of the Cartesian variables of the slave arm end-effector and the submatrices of $\mathbf{P}$. The adaptation law is very computationally efficient because $\mathbf{P}$ is a constant matrix and $\mathbf{x}_e$ can be easily computed from the desired and actual Cartesian variables which are specified by the user and given from position sensors, respectively. Consequently, high sampling rates up to 1 KHz can be utilized in the implementation of the control scheme while the manipulator dynamics can be considered *almost constant* during each sampling interval of typically about 1 ms. Another attractive feature is that the implementation of the control scheme does not require the computation of the manipulator dynamics, which is very difficult, if not possible to model accurately.

3 Computer Simulation Results

This section is devoted to report results obtained from the computer simulation conducted to study the performance of the developed Cartesian-space adaptive control scheme which was applied to control the motion of a RRC K-1607 robot manipulator as shown in Figure 2. The RRC K-1607, manufactured by Robotics Research Corporation is a 7 DOF kinematically redundant manipulator. The manipulator serves as a slave arm of a dual-arm telerobot system recently developed by Goddard Space Flight Center to investigate research issues in telerobotics such as advanced robot control algorithms, dual-arm teleoperation, end-effector design, and hierarchical control using high-level programming languages, etc. The slave arm motion can be controlled in a teleoperation mode by a human operator using the master arm system or autonomously controlled by a set of computer programs. A complete analysis of forward kinematics and differential motion of the RRC K-1607 can be found in [11]. Following the convention in [12], 8 coordinate frames are assigned to the manipulator as illustrated in Figure 2 showing the manipulator in its home configuration with all joint angles being zero. Each ith frame {i} is characterized by its coordinate axes $\mathbf{x}_i$, $\mathbf{y}_i$, $\mathbf{z}_i$ and its origin $\mathbf{0}_i$ for i = 0,1,2,...,7. The Denavit-Hartenberg parameters are given in the following table:

i	α_{i-1}	a_{i-1}	d_i	θ_i
1	0^o	0.000in	0.0in	θ_1
2	-90^o	0.000in	0.0in	θ_2
3	90^o	5.625in	27.0in	θ_3
4	-90^o	4.250in	0.0in	θ_4
5	90^o	-4.250in	27.0in	θ_5
6	-90^o	3.125in	0.0in	θ_6
7	90^o	-3.125in	0.0in	θ_7

Table 1 D-H parameters of the RRC K-1607 manipulator.

For the simulation, ξ_i and ω_i for i=1,2 were selected so that 2 characteristic roots of (10) are -1 and -2. Thus we have $\mathbf{D}_1=2\mathbf{I}_7$ and $\mathbf{D}_2=3\mathbf{I}_7$. Selecting $\mathbf{Q}_i = \mathbf{I}_{14}$ for i=1,2,...,7 and solving (21) gives $\mathbf{P}_2 = \mathbf{P}_3 = 0.25\mathbf{I}_7$. The adaptive controller gains can be now computed by substituting the derived values of $\mathbf{P}_2$ and $\mathbf{P}_3$ into (30)-(31) where $\mathbf{K}_p(0)$ and $\mathbf{K}_d(0)$ can be arbitrarily set. The scalars β_1 and β_2 can be adjusted to improve the tracking quality provided that they are positive values. The payload was set to zero at the beginning of the simulation and suddenly changed to full payload of 10 lb at 1/3 of the simulation time and suddenly dropped to zero again at 2/3 of the simulation time. The sudden change in payload was modeled by delayed step functions. We considered two cases: tracking a straight line and tracking a circular path during a step change in payload. A modified version of Manipulator Simulation Program (**MSP**) [13] was employed for the computer simulation.

Tracking A Straight Line

Figure 3(a)-(b) present the results of the computer simulation in which the robot end-effector was controlled to track a desired straight line in the x-y plane of the base frame. The desired straight line is described by $x(t) = x_0 + 9[1 + 3\exp(-\frac{3.5}{3}t) - 4\exp(-\frac{3.5}{4}t)]$ and $y(t) = y_0 + 9[2 + 6\exp(-\frac{3.5}{3}t) - 8\exp(-\frac{3.5}{4}t)]$ where the initial position is denoted by $x_0 = 33.996in, y_0 = 0in$. According to Figure 3(b), the maximum value of errors in x(t) and y(t) are 0.3473in and 0.1599in, respectively. In addition, the root-mean-square errors of x(t) and y(t) are 0.1536in. and 0.1047in, respectively. Computer simulation results also showed that position errors in z(t) and orientation errors were negligible.

Tracking A Circular Path

Simulation results of the case in which the manipulator end-effector was to track a desired circular path in the x-y plane of the base frame are reported in Figure 4(a)-(b). The circular path consists of 3 segments described by $x(t) = R\cos\Phi_i$; $y(t) = R\sin\Phi_i$ for $t_{i-1} \leq t \leq t_i$ for i=1,2,3 where the circular path radius $R = 24.32in$, $\Phi_1(t) = \phi_0 + \frac{\beta}{2}t^2$, $\Phi_2(t) = \phi_1 + \omega(t - t_1)$, and $\Phi_3(t) = \phi_0 - \frac{\beta}{2}(t_3 - t)^2$ with $\phi_0 = 0in$; $\phi_1 = \Phi_1(t_1)$, angular velocity $\omega = \frac{2\pi}{9} radian/sec$ and the angular acceleration $\beta = \frac{2\pi}{9} radian/sec^2$. Figure 4(b) shows that the maximum value of errors in x(t) and y(t) are 0.6551in and 0.6764in, respectively. Furthermore, the root-mean-square errors of x(t) and y(t) are 0.2730in and 0.3657in, respectively. According to the computer simulation results, position errors in z(t) and orientation errors were negligible.

4 Conclusion

In this report, an adaptive control scheme in Cartesian space was developed to control non-compliant motion of kinematically redundant robot manipulators having 7 DOFs or more. The development of the control scheme employed the concept of model reference adaptive control and the Lyapunov theorem under the assumption that the robot end-effector performs slowly-varying motion. The control scheme was mainly composed of PD controllers whose gains are adjusted by an adaptation law to effectively react to dynamic and static coupling between joints and sudden change in payloads. Computer simulation conducted for two study cases: tracking a straight line and tracking a circular path showed that the developed control scheme provided good tracking quality with root-mean-square errors of about 0.16in for the straight line and about 0.36in for the circular path, despite step changes in payloads. Current research activities focus on implementing the developed control scheme to control the real-time motion of the RRC K-1607 manipulator. Experimental results on the implementation will be given in future reports. A hybrid control scheme is currently under development for simultaneous control of position and force of redundant robots. In addition, utilization of the manipulator redundancy for avoidance of obstacles and joint limits is currently an active research area.

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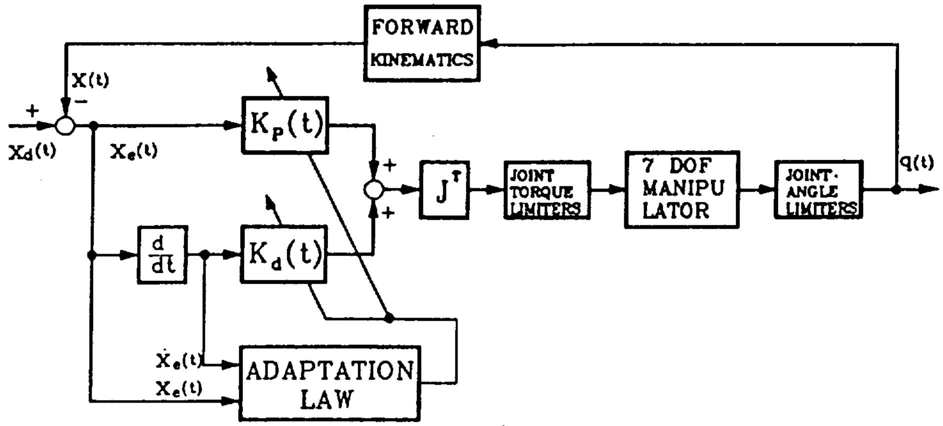

Figure 1 The Cartesian-space adaptive control scheme.

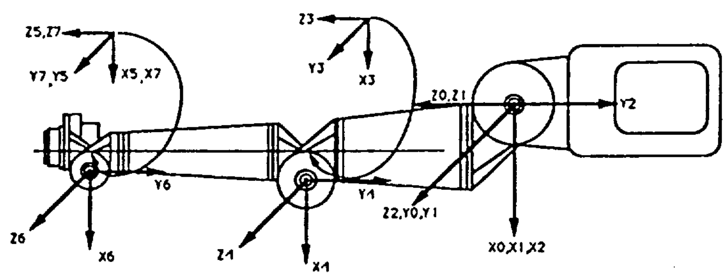

Figure 2 The RRC K-1607 robot manipulator.

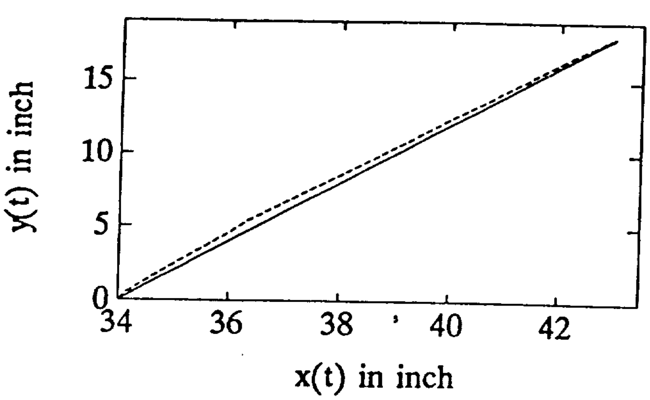

Figure 3(a) Tracking a straight line *(solid=desired; dashed=actual).*

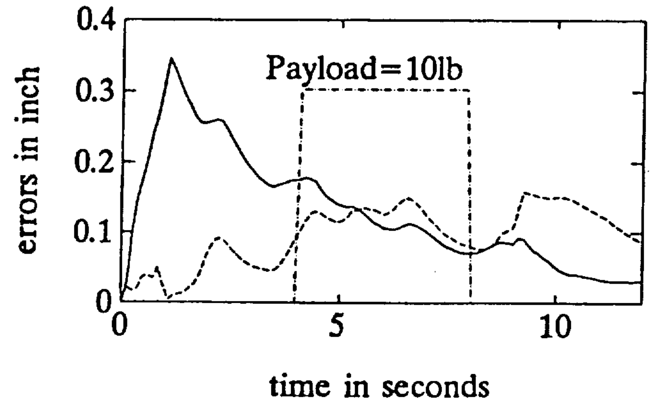

Figure 3(b) Errors in tracking a straight line *(solid=x-error; dashed=y-error)*.

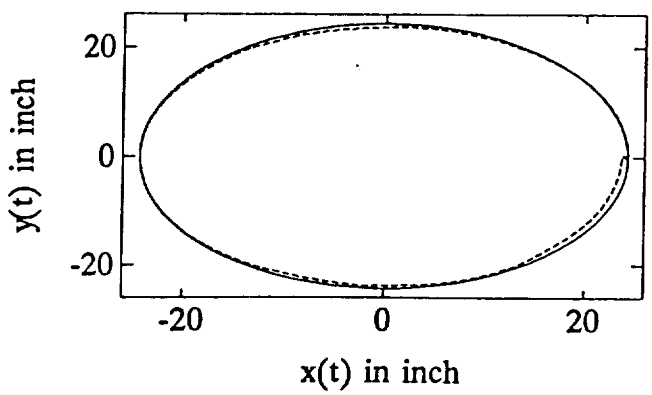

Figure 4(a) Tracking a circular path *(solid=desired; dashed=actual)*.

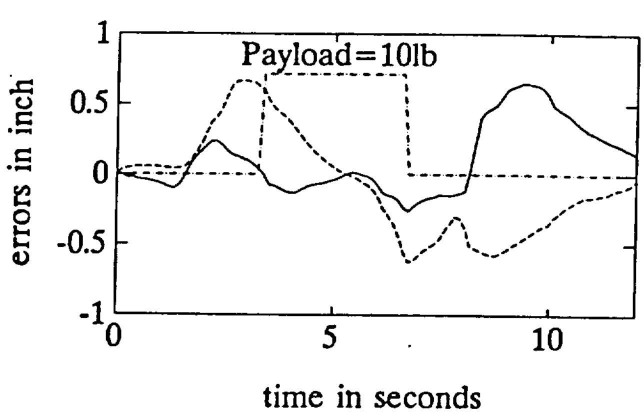

Figure 4(b) Errors in tracking a circular path *(solid=x-error; dashed=y-error)*.